Australian Government
Department of Defence
Defence Science and
Technology Organisation

A Co-axial Test Cell for Measuring the Electrical Parameters of a Sample of the Ground Surrounding a HF Antenna Installation

W. Martinsen

Command, Control, Communications & Intelligence Division
Defence Science and Technology Organisation

DSTO-TR-2555

ABSTRACT

This report describes the development of a co-axial test cell for measuring the electrical parameters of ground samples taken from an antenna site. The accuracy of the test cell has been verified by measuring the relative dielectric constant of air and distilled water over the HF frequency range. The resistivity measurement equation has been confirmed by measuring a calibrated test solution at 10 KHz.

RELEASE LIMITATION

Approved for public release

Published by

DSTO Defence Science and Technology Organisation
PO Box 1500
Edinburgh, South Australia, 5111 Australia

Telephone: (08) 7389 5555
Fax: (08) 7389 6567

AR 015-010
June 2011

APPROVED FOR PUBLIC RELEASE

A Co-axial Test Cell for Measuring the Electrical Parameters of a Sample of the Ground Surrounding a HF Antenna Installation

Executive Summary

Vertical monopole antennas are commonly used for their low radiation angle and omni-directional pattern for site noise measurements in the HF band. The ground around the antenna installation interacts with the antenna modifying its feed-point impedance and losses. The losses are usually seen as a reduction in the gain of the antenna. Accurate HF noise field intensity measurements, or any field strength measurement, can only be made if the gain of the antenna is known to a corresponding fidelity.

Antenna simulation software using the Sommerfeld/Norton ground model can be used to calculate the feed point impedance and gain of an antenna in its installed environment. This software requires accurate knowledge of the electrical parameters of the ground surrounding the installation. The test cell described in this report can be used to measure the HF electrical parameters of the ground thereby enabling the simulation software to calculate the antenna gain. Accurate noise field intensity measurements can then be made using the calculated antenna gain and a calibrated receiver.

This page is intentionally blank

Author

W. Martinsen
Command, Control, Communications and Intelligence Division

Wayne Martinsen was indentured as an apprentice communications technician in 1972 with Transport Communications Pty. Ltd.(Buranda, Qld.). He attended Yeronga Technical College (Brisbane, Qld.) where he received honours in the majority of his subjects. In 1975 his apprenticeship indentures were transferred to The Radio Centre (Archerfield Aerodrome, Qld.) where he was employed as an Air Maintenance Engineer, Category Radio. He was involved in all aspects of repair and maintenance of avionics systems associated with the light aircraft industry. Upon completing his training as an apprentice he sat for and passed various Dept. of Transport Licensed Air Maintenance Engineer (L.A.M.E.) exams. In 1977 he joined the RAAF and after graduating from their School of Radio, where he received training in military systems, he worked on a wide variety of airborne communications, navigation and anti-submarine warfare systems. In 1987 he was discharged from the RAAF and applied for a position with DSTO at Edinburgh, South Australia. He was offered and accepted the position of Technical Officer (Engineering). Here he was tasked with the design and development of R.F. circuits required for tropospheric and ionospheric research.

This page is intentionally blank

Contents

This page is intentionally blank

1. Introduction

Vertical monopole antennas are commonly used for site noise measurements in the high frequency (HF) band because of their low-angle radiation pattern and omni-directional coverage. For instance, the widely-used noise figures compiled by the CCIR [8] were measured using a short vertical antenna, scaled under the assumption of a lossless antenna situated on a perfect ground plane. While such tabulated noise statistics are useful in many applications, accurate HF noise field intensity measurements, or any absolute field strength measurement, can only be made if the gain of the antenna is known to a corresponding fidelity. This is in practice a nontrivial requirement because the ground around the antenna installation interacts with the antenna, modifying its feed-point impedance and losses; these losses are usually manifested as a reduction in the gain of the antenna.

The electrical parameters which influence the antenna gain are :

- relative permittivity (ε_r) also known as relative dielectric constant,
- relative permeability (μ_r) considered to be unity unless there is magnetic material in the ground and
- conductivity (σ) measured in S/m.

Thus, at a minimum, the ε_r and σ of the ground in the vicinity of an antenna installation need to be measured so the effects they have upon the antenna gain can be calculated. Antenna simulation software, such as GNEC with the NEC4 core invoking the Sommerfeld/Norton ground model, can then be used to calculate the feed point impedance and gain of an antenna in its operational environment.

The test cell described in this report has been designed to measure the electrical parameters of interest at HF to high accuracy whilst retaining a compact, robust, portable form eminently suited to operation in the field. In the course of its development, several alternative methods of measuring ground parameters (Wenner, the inverted monopole and the buried parallel wire transmission line as described in Appendix B) were tried. These methods did not produce consistent results when their probe lengths and/or spacing were changed. Only the co-axial test cell returned results that, when fed into NEC4, returned computed data from an antenna simulation that was very close to that measured on a HF monopole antenna installed on the DSTO Edinburgh (DSTOE) test site. Moreover, half filling the co-axial test cell with a ground sample and adjusting the equations appropriately returned results for ε_r and σ that were almost identical to the same cell as if it were completely filled. This gives a degree of confidence both in the equations used and the co-axial test cell methodology.

2. The co-axial test cell

Figure 1 shows the prototype test cell. It was constructed using two aluminium cylinders 200 mm long with 1.8 mm wall thickness, one 96 mm inside diameter (ID) the other 50.6 mm outside diameter (OD). The cylinders are held in a co-axial configuration by a machined TUFNOL®[1] base.

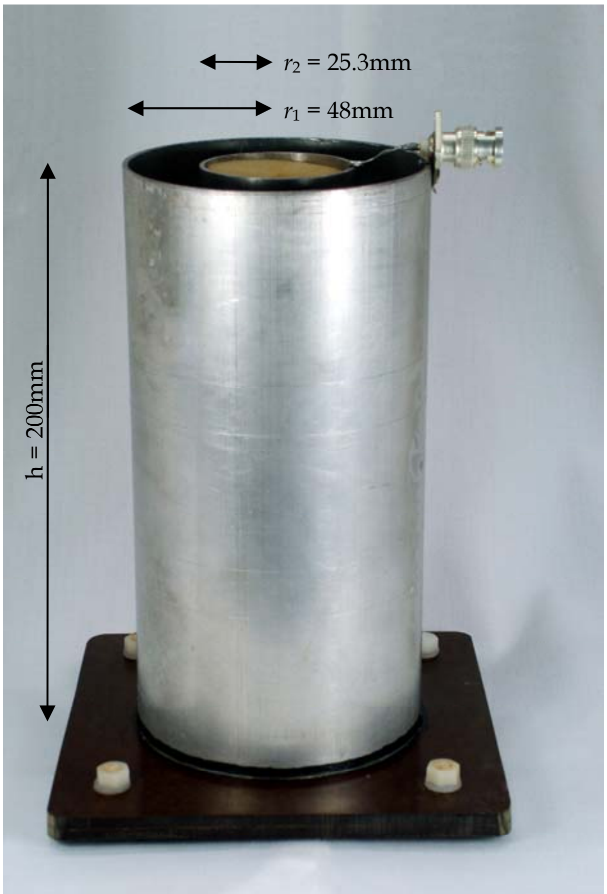


Figure 1: The co-axial test cell mounted on a machined TUFNOL base with the clip-on BNC connection

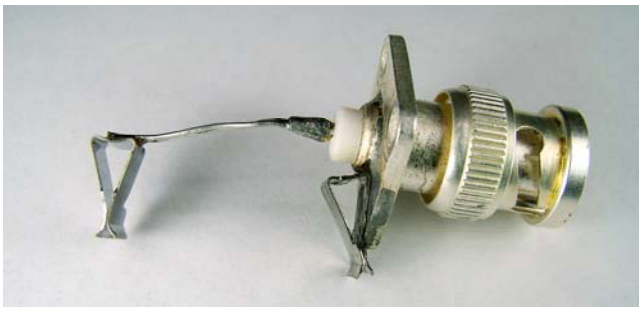


Figure 2: Co-axial test cell's clip-on BNC connector with flying lead

[1] TUFNOL® is a phenolic paper laminate

The soil sample, which must be free from stones, gravel, wood chips and other foreign objects, is placed in the space between the two cylinders and packed with a ramming rod to the approximate consistency of the undisturbed ground. The ground sample must be placed in the test cell immediately after extraction to minimize the sample's moisture loss due to evaporation.

Figure 2 shows the removable BNC connector and flying lead with stainless steel spring clips soldered to them. The spring clip is a standard 'EXP128 Clip Refills', available from most stationary suppliers, which has been cut in half and soldered to the connector and lead. This attachment method returns consistent values of distributed inductance which is necessary for accurate calibration.

2.1 Calculating conductivity (S/m)

Conductivity measurements are usually carried out by placing a test voltage/signal to plate electrodes covering two parallel surfaces of a cube of the sample material. The conductivity can then be defined by Ohms law; i.e. a current I (in Amps) passing through a block of the material, of area A and length l, is related to the voltage E applied to the plate electrodes covering two parallel faces of the cube by:

$$R = \frac{E}{I} = \frac{\rho l}{A} = \frac{l}{\sigma A} \tag{1}$$

re-arranging for conductivity:-

$$\sigma = \frac{l}{RA} \tag{2}$$

and deriving its unit of measure:-

$$= \frac{l}{RA} = \frac{1}{\Omega} \cdot \frac{m}{m^2} = S \cdot \frac{1}{m} = \text{S/metre}$$

where:-
- E = volts
- I = current (A)
- R = resistance (Ω)
- A = area (m^2)
- l = length (m)
- ρ = resistivity (Ω-metres)
- σ = conductivity (S/m)

Although the unit of measure is cited in S/m or S/cm it should be remembered that the dimension refers to a measurement made on the unit cubic volume, not just a length.

Equations for calculating the soil parameters using the co-axial test cell are derived from the following expression [4, pg. 2, equation (5)]. It describes a measurement carried out by placing a cube of the sample material between the parallel plates of a capacitor.

$$R_p C_p = \frac{\varepsilon}{\sigma} = \frac{\varepsilon_o \varepsilon_r}{\sigma} \tag{3}$$

where: R_p = shunt resistance (Ω)
C_p = shunt capacitance (F)
ε = ε_o ε_r (F/m)
ε_o = free space permittivity = 8.854E-12 Farads/metre
ε_r = relative permittivity

Re-arranging equation (3) to solve for conductance gives:

$$\sigma = \frac{\varepsilon_o \varepsilon_r}{R_p C_p} \tag{4}$$

2.2 Calculating relative dielectric constant

The soil's relative dielectric constant is readily calculated from the increase in capacitance of the cell from when air is the filling medium to that of the ground sample. The capacitance of the test cell with air filling the space between the cylindrical plates can be calculated using equation (5) [6, ch. 6 pg. 15]

$$C_a = \frac{2\pi h 8.854\times 10^{-12}}{\ln\left(\frac{r_1}{r_2}\right)} \quad \text{(F)} \tag{5}$$

where: C_a = 17.37E-12 = capacitance of co-axial test cell when filled with air (F)
h = 0.2 = height of cylinder (m)
r_1 =0.048 = inner radius of outer cylinder (m)
r_2 = 0.0253 = outer radius of inner cylinder (m)

The relative dielectric constant of the sample is calculated by dividing the measured capacitance of the test cell when filled with a ground sample (C_p) by the capacitance of the cell when filled with air (C_a).

$$\varepsilon_r = \frac{C_p}{C_a} \tag{6}$$

where: C_a = calculated cell capacitance when filled with air, equation (5) (F)
C_p = measured shunt capacitance of ground sample (F)

2.3 Test cell's measured data reduction steps

Equations (4) and (6) require the resistance and capacitance in their parallel form however, most field type RF impedance meters give the measured resistance and reactance in series form, R_s and X_s respectively. Figure 3 shows the steps that need to be taken in order to convert these measured values into the required R_p and C_p. The dotted bounding outline indicates components that are grouped together that give the value of combined reactance. These are the test cell's distributed and fringing capacitance and the distributed inductance. The distributed inductance makes the capacitance appear larger with increasing frequency than it really is; hence the term $X_{s(apparent)}$ next to the bounding box. In Figure 3(b) the effects of the distributed inductance have been removed so the true value of capacitive reactance can be realised. A series to equivalent parallel circuit conversion is carried out to give the component values required by equation (4), Figure 3(c). The true capacitive reactance $X_{p(true)}$ in Figure 3(c) is the reactance of the total capacitance of the test cell i.e. the distributed plus fringe capacitance. The fringe capacitance does not change in value when the test cell is filled with a ground sample and therefore needs to be removed. The expected test cell capacitance is calculated from first principles and subtracted from the measured capacitance of the cell when air is the filling medium, the remainder being the fringing capacitance. This measurement is usually carried out at some very low frequency before the effects of the cell's distributed inductance makes the cell's capacitance appear larger than it really is. In Figure 3(d) the fringe capacitance has been subtracted giving C_p and R_p, the two quantities required in equations (4) and (6).

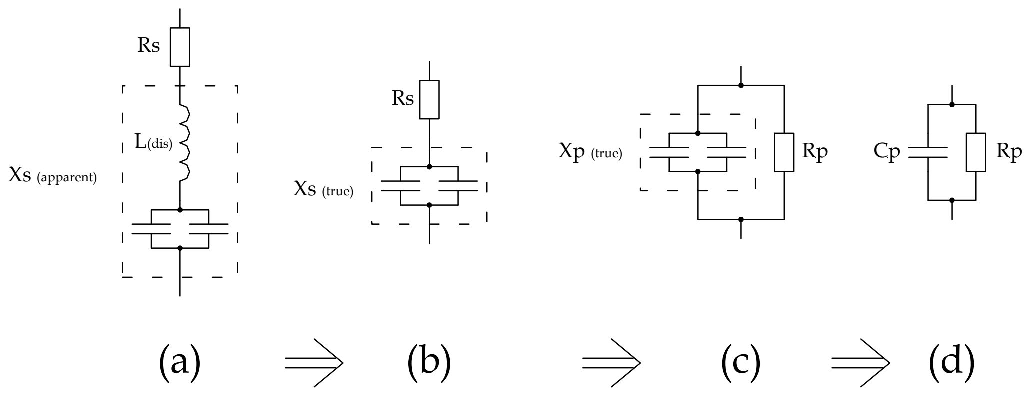


Figure 3: Process steps required on the raw data to obtain the values of C_p and R_p

2.4 Calibrating the co-axial test cell

The two quantities that need to be known in order to calibrate the test cell are,

1. the distributed inductance ($L_{(dis)}$) of the test cell and its connecting leads used to connect the cell to the network analyser. The distributed inductance gives a frequency dependency to the sample's measured apparent capacitance. Errors introduced by the distributed inductance are predominant when measuring soil samples with high relative dielectric constants at high frequencies. These errors reduce as the measuring frequency is lowered for a given sample or when measuring samples with a lower relative dielectric constant.

2. the value of the test cell fringing capacitance. The fringing capacitance, which is seen in red in Figure 4, does not change in value when the test cell is filled with the soil sample. Its total value is dependant upon the relative dielectric constants of the machined TUFNOL® base at the bottom and air at the top. Errors introduced by the fringing capacitance have the greatest effect when measuring samples with very low relative dielectric constants; this error diminishes as samples with higher relative dielectric constants are measured. There are four rubber feet at the bottom of the TUFNOL® base. These feet provide an air gap between the bottom of the test cell and the surface that it is sitting on. This air gap helps to reduce the effects different surfaces may have on the fringe capacitance seen at the TUFNOL® base.

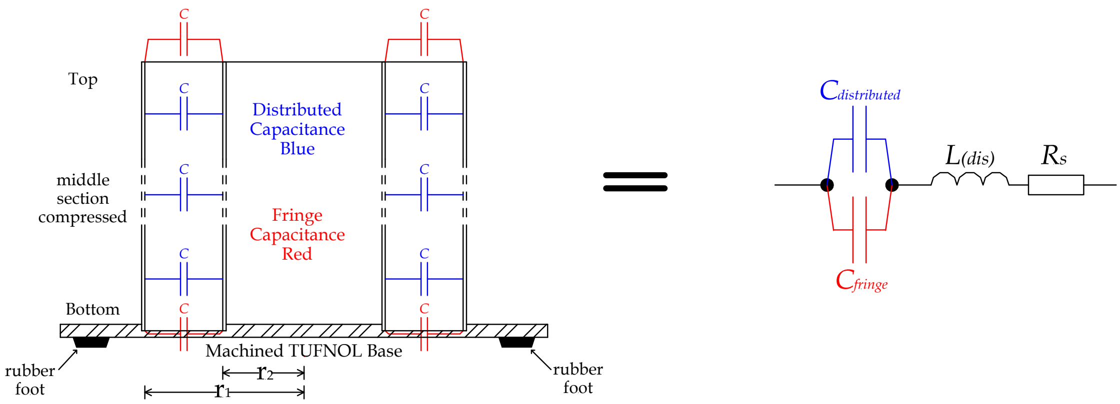


Figure 4: Cross-sectional view of the co-axial test cell mounted on a machined TUFNOL base showing the distributed capacitances and the cell's equivalent electrical circuit

2.4.1 Calculating $X_{s(true)}$ the reactance of the true series capacitance

The distributed inductance is calculated from the cell's measured capacitance at 1 MHz (or less) and the cell's measured series resonant frequency. Equation (12) is then used to calculate the distributed inductance.

$$L_{(dis)} = \frac{1}{4\pi^2 f_r^2 C_{(measured)}} \quad \text{(H)} \qquad (7)$$

where: $L_{(dis)}$ = cell's distributed inductance (31.5nH) (H)

f_r = cell's measured series resonant frequency (approx. 198 MHz for the current cell) (Hz)

$C_{(measured)}$ = cell's measured distributed capacitance (20.5 pF for the current cell measured at 1 MHz) which includes the fringe capacitance (F)

Instrument measurement errors do exist in the measured series resonant frequency due to the very small value of distributed inductance involved. Slight changes to the resonant frequency are made in a future calibration step to compensate for the measurement errors to obtain a more accurate value for the distributed inductance.

The reactance of the distributed inductance needs to be appropriately added to or subtracted from the measured $X_{(apparent)}$ to find $X_{S(true)}$, the true capacitive reactance of the cell, equation (9). $X_{(apparent)}$ as measured on a network analyser will be negative if capacitive or positive if inductive.

$$X_{L_{(dis)}} = 2\pi f L_{(dis)} \qquad (\Omega) \qquad (8)$$

$$X_{S(true)} = X_{L_{(dis)}} - \left(\pm X_{(apparent)}\right) \qquad (\Omega) \qquad (9)$$

2.4.2 Converting from series to parallel

$X_{s(true)}$ together with R_s are converted into their parallel equivalent form via [10, ch. 24, pg. 12];

$$R_p = \frac{R_s^2 + X_{s(true)}^2}{R_s} \qquad (\Omega) \qquad (10)$$

$$X_{p(true)} = \frac{R_s^2 + X_{s(true)}^2}{X_{s(true)}} \qquad (\Omega) \qquad (11)$$

Equation (11) returns the cell's total true capacitive reactance in parallel form $X_{p(true)}$ which includes the fringe capacitance.

2.4.3 The fringe capacitance

Most of the fringing capacitance is due to the machined TUFNOL® base used to hold the co-axial cylinders in place. It is found by subtracting the capacitance calculated via equation (5) from the measured value.

$$C_{(fringe)} = C_{(measured)} - C_a \qquad (F) \qquad (12)$$

$$C_{(fringe)} = 20.5\text{pF} - 17.37\text{pF} = 3.13\text{pF}$$

$C_{(measured)}$ is usually measured at a frequency not exceeding 1 MHz. At higher frequencies the cell's distributed inductance will affect the capacitance reading. Once $C_{(fringe)}$ is known it is subtracted from the cell's measured capacitance of the sample filling the space between the two cylinders.

2.4.4 Calculating C_p

C_p is calculated by converting $X_{s(true)}$ into capacitance then subtracting $C_{(fringe)}$.

$$C_p = \frac{1}{2\pi f X_{p(true)}} - C_{(fringe)} \qquad \text{(F)} \qquad (13)$$

2.4.5 Calibrating the test cell's measurement volume

The conductivity of equation (4), when applied to the co-axial test cell, is for a volume defined as the distance between the two surfaces times the geometric mean area of the two internal surfaces in the co-axial measurement cell.

$$test\ cell\ volume = (r_1 - r_2)\left(2\pi\sqrt{r_1 r_2}\right)h$$

This volume needs to be appropriately scaled to 1 m^3 to suit the requirements of equation (1). Equation (1) shows the resistance is proportional to the length of the electrical circuit and inversely proportional the circuit's cross-sectional area. For the test cell, distance (r_1-r_2) is the circuit length and $\left(2\pi\sqrt{r_1 r_2}\right)h$ is the circuit's cross-sectional area. The final equation for conductivity in S/m for the test cell described in Figure 1 is:

$$\sigma = \frac{\varepsilon_o \varepsilon_r}{R_p C_p}\left(\frac{r_1 - r_2}{h 2\pi\sqrt{r_1 r_2}}\right) \qquad \text{(S/m)} \qquad (14)$$

where:

	R_p	= shunt resistance calculated from equation (10) (Ω)
	C_p	= shunt capacitance calculated from equation (13) (F)
	ε_o	= free space permittivity = 8.854E-12 Farads/metre
	ε_r	= relative permittivity calculated from equation (6)
	r_1	= inner radius of outer co-axial cylinder (m)
	r_2	= outer radius of inner co-axial cylinder (m)
	h	= height of co-axial cylinder (m)

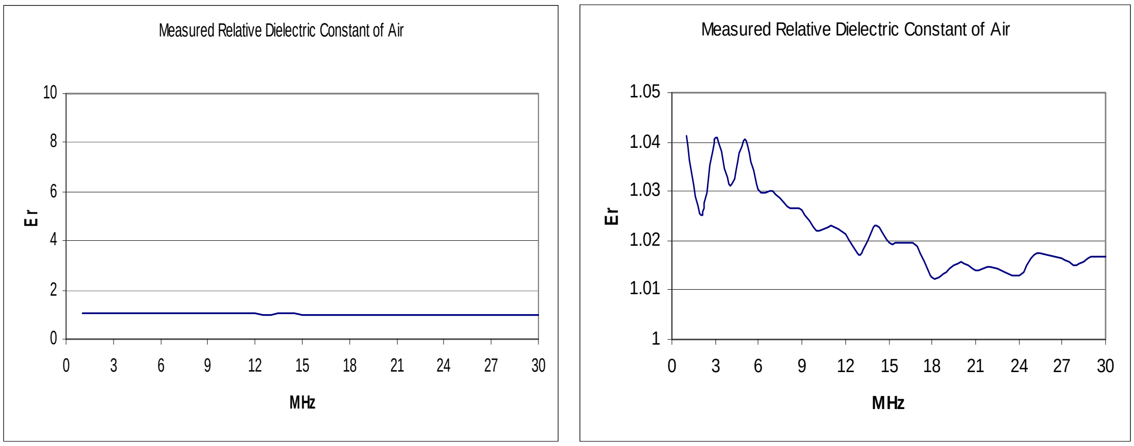
2.4.6 Adjusting the measured series resonant frequency to fine tune the distributed inductance

Water from rain absorbed by the ground is the main element affecting the ground's parameters. The relative dielectric constant (ε_r) of distilled water is 78.2 at 1 MHz and 78 at 100 MHz [6, ch. 4 pg. 22]. Distilled water is therefore the ideal compound to calibrate the test cell. The test cell was made watertight by applying a thin bead of sealant to the portion of the TUFNOL® base that comes in contact with the co-axial cylinders. Distilled water was poured into the space between the two cylinders and measurements were made from 1 MHz to 30 MHz in 1 MHz increments. Equations (5) to (14) were entered into an EXCEL spreadsheet to make the calculations and plot ε_r. The calculated ε_r for distilled water should be a straight horizontal line when plotted with frequency on the X axis. If the line bends either up or down as the frequency is raised then the value of distributed inductance as calculated in equation (7) needs to be corrected. The most probable cause is the network analyser's inability to accurately measure very small values of inductance. Slight changes in the test setup can shift the cell's series resonance several MHz. The initial measurement of 198 MHz which was entered into equation (7) was finely adjusted in the EXCEL spreadsheet until settling on 194.8 MHz, which resulted in a horizontal line for the ε_r plot. The distributed inductance of 32.6 nH calculated using equation (7) is the key parameter needed to find the cell's true measured capacitance as a function of frequency.

Figures 5 and 6 show the results of the EXCEL spreadsheet for air and water respectively as the media being measured. The Y axis on both plots has been 'zoomed-in' to show the detailed measured value's variation with frequency. The measured relative dielectric constant of air being slightly greater than one is expected. This is due to the presence of moisture in the air. No relative humidity measurement of the air in the lab was taken on the day so its effects could not be subtracted from the measurement. The measured accuracy of +4% or better from an expected $\varepsilon_r = 1$ was deemed sufficient for most practical applications. Similarly, the amount of air both dissolved and in suspension in the distilled water sample, which will slightly lower the water's relative dielectric, was also not considered. The measured accuracy of -1% for the relative dielectric constant of water with respect to the expected value of 78.2 over the HF band was deemed more than sufficient.

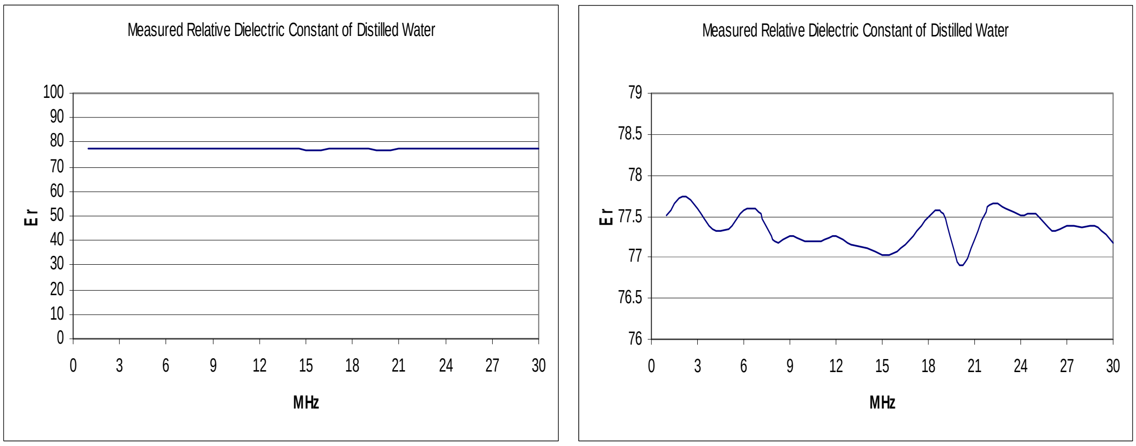
2.5 Checking the conductivity equation

HI-7033 is a laboratory grade conductivity calibration solution made by Hanna Instruments. It has a conductivity of 84 μS/cm at 25ºC. The test cell was filled to a height of 0.185 m and the temperature of the solution measured and found to be to be 21.6ºC. The calibration scale on the bottle label indicates the conductivity of the solution at this temperature is 78.6 μS/cm (or 0.00786 S/m). The stated conductance of the solution was checked with a Hanna HI 8733 conductivity meter. A MOTECH MT 4080A handheld LCR meter was used to measure an AC resistance of 71.59 Ω at 10 KHz for the co-axial test cell containing the conductivity solution. Equation (15) which is a simplified version of equation (14) was used to convert this measurement to S/m.



(a) (b)

Figure 5 *Measured relative dielectric constant of air versus frequency (a) showing a relatively straight line and (b) 'zoomed-in' to show the variation in the measured data*



(a) (b)

Figure 6 *Measured relative dielectric constant of distilled water versus frequency (a) showing a relatively straight line and (b) 'zoomed-in' to show the variation in the measured data*

$$\sigma = \frac{r_1 - r_2}{R 2\pi h \sqrt{r_1 r_2}} \qquad \text{(S/m)} \qquad (15)$$

where:

σ = 0.00783 (S/m) = measured conductance of calibration solution
R = 71.59 (Ω) = measured resistance of calibration solution at 10 KHz
r_1 = 0.048 (m) = inner radius of outer co-axial cylinder
r_2 = 0.0253 (m) = outer radius of inner co-axial cylinder
h = 0.185 (m) = height of calibration solution in co-axial cylinder

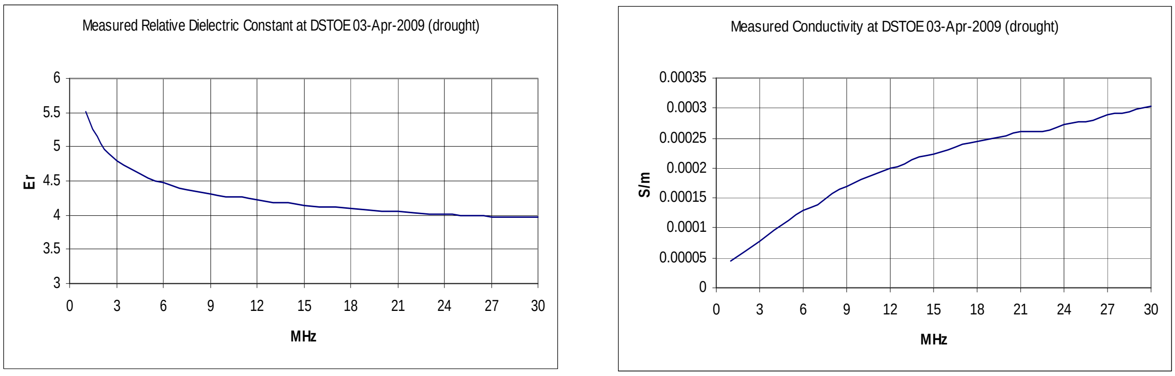
Substituting the above values into equation (15) yields a conductance of 0.00783 S/m which is in good agreement with the cited conductivity of 0.00786 S/m under the conditions measured and confirms equation (14).

2.6 Measurements made using the co-axial test cell at the DSTOE antenna site

The co-axial test cell was used to make two measurements at an antenna site at DSTOE. The first measurement was performed on 03-Apr-2009 at the end of a long drought before the winter rains. The ground was very dry and hard to dig. The second was at the same spot after several weeks of prolonged rain in the middle of the winter rains. The ground was very moist though some effort was still required to dig up the sample. Figures 7 and 8 show the measured results. These measurements represent the two extremes of the ground's relative dielectric constant and conductivity versus seasonal changes.

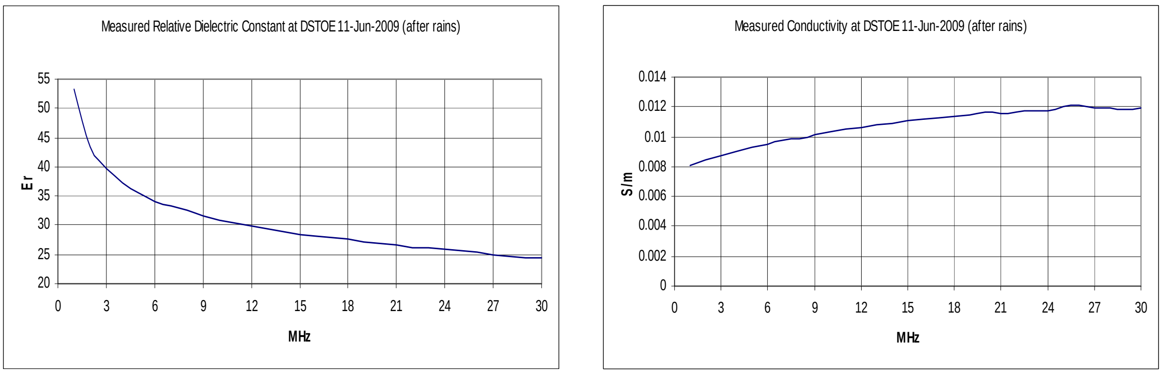
The impedance of a 6.5 m vertical monopole installed at the location where the samples were taken was measured to be 45.7 Ω at a resonant frequency of 11.27 MHz, using an Agilent N9912A handheld network analyser as shown in Figure 9. The Agilent N9912A outputs saved data in the S_{11} (REAL) and S_{11} (IMAGINARY) format. The equations listed in Appendix A were used to convert the measured data into the equivalent series circuit of R_s and jX_s, which could then be used in the calculations. The ground parameters measured at 11 MHz by the co-axial test cell as shown in Figure 8 are $\varepsilon_r = 30.3$ and $\sigma = 10.5$ mS/m. The vertical monopole was modelled using GNEC with these measured ground parameters in the Sommerfeld/Norton ground model. GNEC returned a radiation resistance at resonance of 46.2 Ω which is in excellent agreement with the measured 45.7 Ω.

Figure 10 shows the monopole antenna's gain relative to isotropic, as simulated by GNEC for the ground parameters measured at the DSTOE antenna site in April and June 2009 and also for a perfect ground plane. The length of the antenna in the simulation was adjusted with the various ground models to bring the antenna to resonance at 11.27 MHz.



(a) (b)

Figure 7 *(a) Measured relative dielectric constant and (b) conductivity at the DSTOE antenna site on the 03-Apr-2009 during the last weeks of a prolonged drought*



(a) (b)

Figure 8 *(a) Measured relative dielectric constant and (b) conductivity at the DSTOE antenna site on the 11-Jun-2009 after several weeks of heavy rain breaking the drought*

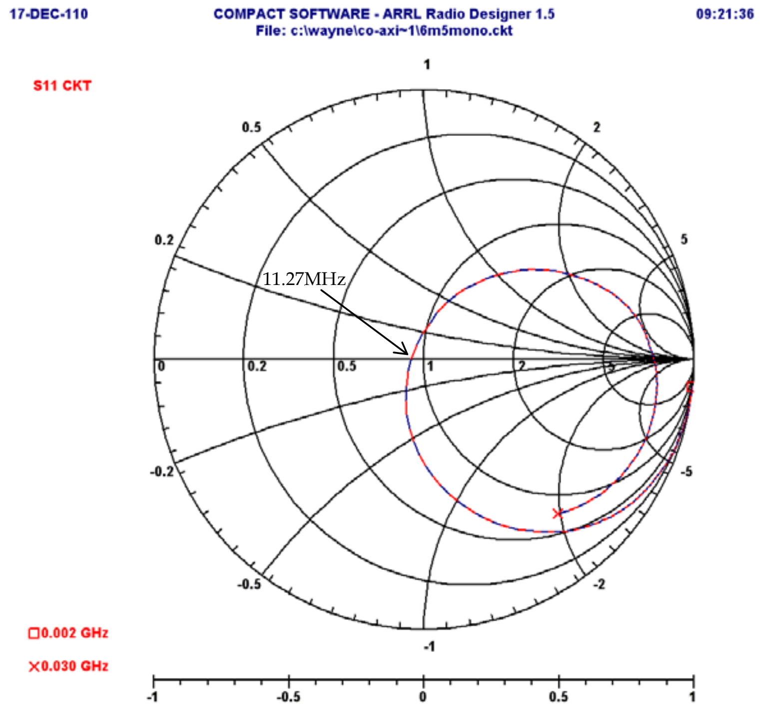


Figure 9: *Measured response from 2 to 30 MHz of the 6.5 m monopole antenna (ε_r = 30.3 and σ = 10.5 mS/m). ARRL Radio Designer used as a graphical interface for data collected on the Agilent N9912A handheld network analyser.*

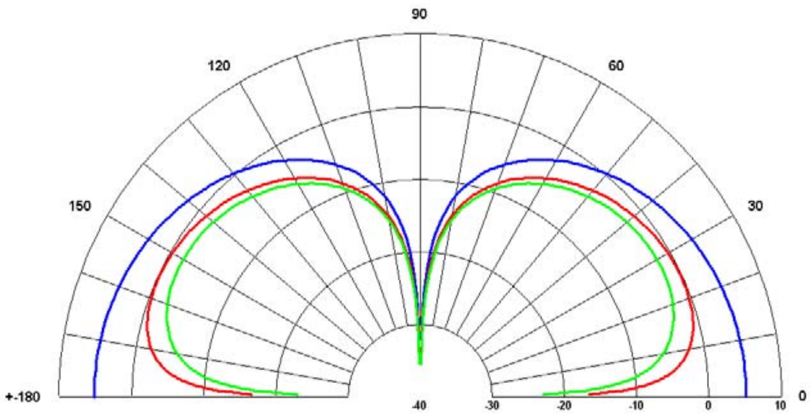


Figure 10: *Simulated gain in dBi of the 6.5 m resonant monopole at 11.27 MHz using GNEC*
Blue:- on a perfect ground plane, maximum gain 5.1 dBi at 0 degrees elevation
Red:- (after rains) with ε_r = 30.3 and σ = 10.5 mS/m in the Sommerfeld/Norton ground model, maximum gain is -0.24 dBi at 25 degrees elevation
Green:- (drought) with ε_r = 4.3 and σ = 0.19 mS/m in the Sommerfeld/Norton ground model, maximum gain is -2.1 dBi at 30 degrees elevation

2.7 Calculating skin depth and relative attenuation

Data from the co-axial test cell can also be used to calculate the skin depth and relative attenuation of an electromagnetic wave in the ground. The following equations can be used to calculate the skin depth and relative attenuation respectively [7, pg. 146 to 149].

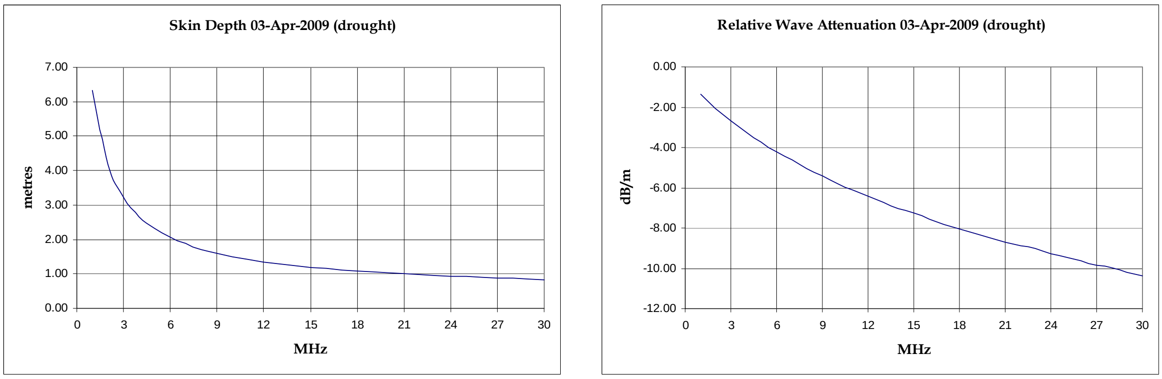
$$\delta = skin\ depth = \frac{1}{\alpha} = \frac{1}{\omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{\frac{1}{2}}} \qquad \text{(m)} \qquad (16)$$

$$\text{relative attenuation} = -8.68\alpha \qquad \text{(dB/m)} \qquad (17)$$

where:- α = attenuation constant (Np/m)
ω = $2\pi f$ = radial velocity (rad/s)
f = frequency (Hz)
μ = $\mu_o\mu_r$
μ_o = 1.257E-6 (H/m)
μ_r = relative permeability (assumed to be 1 for soils with low iron content)
ε = $\varepsilon_o\varepsilon_r$
ε_o = 1.3806E-23 (F/m)
ε_r = relative permittivity
σ = conductivity (S/m).

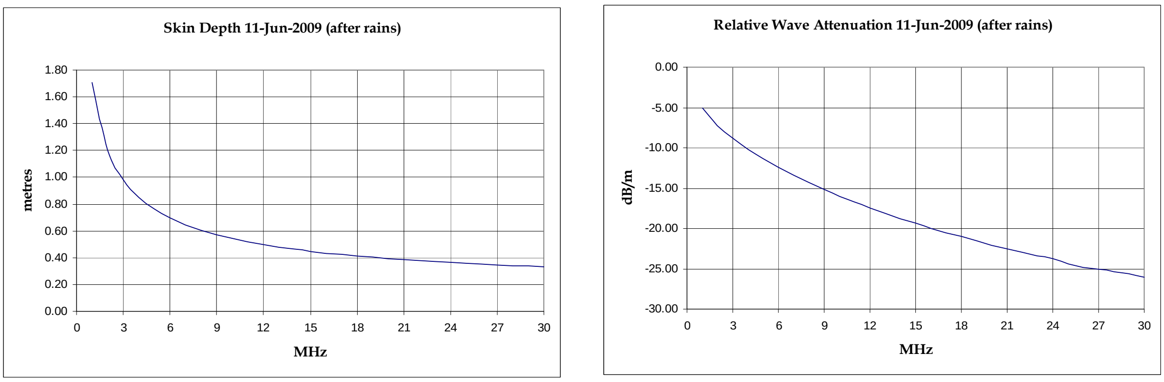
These equations together with the data obtained from Figures 8 and 9, were inserted into an EXCEL spreadsheet to generate Figures 11 and 12. Figure 11 is the skin depth in metres and relative wave attenuation in dB/m for the ground conditions on 03-April-2009 when the ground was very dry and Figure 12 is the same ground after two months of winter rains (note the different vertical scales).

It is worth noting that the observed skin depth under dry conditions exceeded 1 m for all frequencies up to 20 MHz, and reached 3 m at 3 MHz. It is usually the case that the ground is not homogeneous over such a large depth range, so ideally one should determine ground electrical properties as a function of depth. A key virtue of the co-axial test cell is that it permits profile sampling, whereas other methods, such as those described in Appendix B, are essentially limited to an integrated measurement.



(a) (b)

Figure 11: Results of equations (16) and (17) using data from Figure 7 (03-April-2009), (a) is the skin depth in metres and (b) the relative wave attenuation in dB/m



(a) (b)

Figure 12: Results of equations (16) and (17) using data from Figure 8 (11-June-2009), (a) is the skin depth in metres and (b) the relative wave attenuation in dB/m

2.8 Sample Preparation

If there is a weakness with the proposed technique in its basic form, it relates to the need to pack the collected soil sample into the annular test volume. At present the original packing density is recreated, or at least approximated, by tamping the sample progressively during the filling operation. A test was carried out to see the variation in measurements between lightly tamping the sample into the test cell versus heavy ramming. The soil sample was first lightly tamped into the test cell and measurements were taken. The packing density of the sample was such that the 150 mm shaft of a 6.5 mm flat blade screwdriver could, with some force, be pushed into the sample up to its handle. The test cell was then emptied into the hole in the ground where the sample was taken from and then repacked into the test cell, this time progressively rammed as the cell was being filled. The screwdriver could only be pushed some 15 to 20 mm into the sample using considerable force when the sample was heavily rammed. A hammer would be needed to drive the screwdriver any deeper. The force required to push the screwdriver into the soil sample is compared with the force needed on the undisturbed soil and is used to approximate the packing density. This heavy ramming closely approximates the density of the undisturbed soil. The screwdriver is also used to chisel the heavily rammed soil sample out of the test cell after measurements are made. The test cell was then emptied and repacked, progressively ramming, another four times with measurements taken. This was done to see if there was any variation in the measurements due to slight variations in the ramming technique. Figure 13 and 14 show the results.

Figure 13 shows the variation in ε_r with frequency across the HF band. The lightly tamped sample has the lowest ε_r as expected. This is due to tiny pockets of air, an ε_r of one, displacing the soil sample lowering the average value. The gradual decrease of the measured ε_r from Heavy Ram 1 to Heavy Ram 5 in the lower part of the HF band is expected and is attributed to the loss of moisture from the soil sample as it was progressively exposed to the air when transferred to and fro between the test cell and the hole in the ground. In the upper part of the HF band Heavy Ram 1 to 3 probably reflect the variations in packing density whereas in 4 and 5 the moisture loss appears to dominate. The slight step in the data at 24.8 MHz is an artefact of the Agilent N9912A handheld network analyser. A second N9912A instrument has a slightly smaller step at the same frequency.

Figure 14 shows the variation in conductivity across the HF band. The light tamping having the lowest conductivity is expected. Tiny pockets of air, being an insulator, had displaced some of the moisture laden soil sample lowering the average conductivity. The Heavy Ram 1 to 5 plots are not unexpected and clearly show the progressive loss of moisture from the sample during the approximate one hour duration it took to do all six measurements.

A better approach to digging and tamping the sample into the test cell is to collect the sample directly as an annular core, requiring much less disturbance to the original soil sample. This would require the expense of developing a special annular drilling and core extraction tool. Another possibility is to use the annular drilling bit itself as the test cell which would negate the need to extract the core sample from the ground. These specialized tools would speed-up the measurements and are ideally suited to a very large HF antenna array installation. The current requirement is for a small test facility and therefore could not justify either the time or expense to develop such a tool.

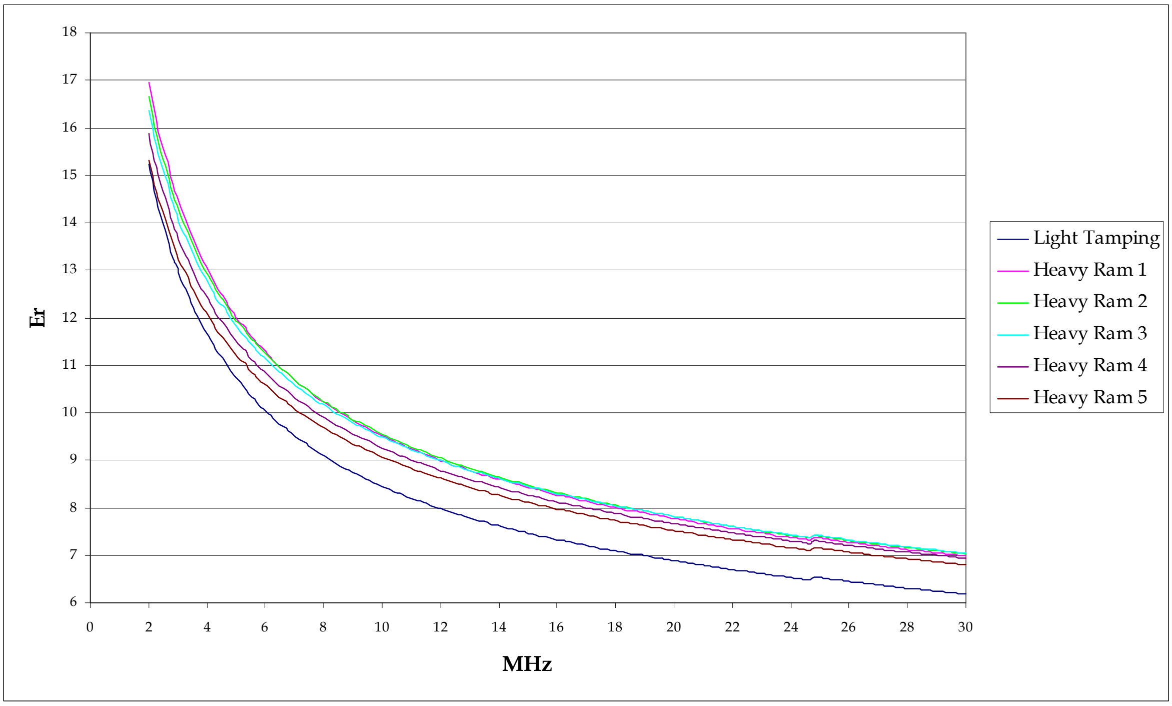


Figure 13: Variation in measured ε_r when the soil sample is tamped and rammed into the test cell

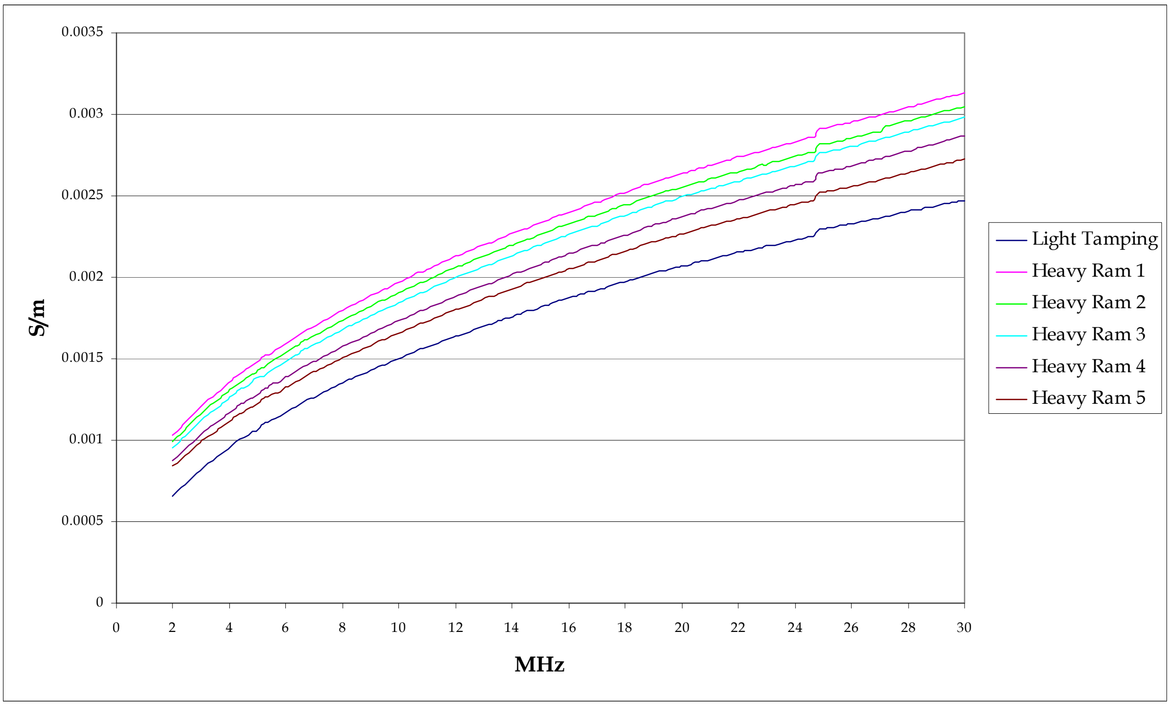


Figure 14: Measured variation in conductivity when the soil sample is tamped and rammed into the test cell

3. Conclusions

A ground parameter co-axial test cell has been presented. It is constructed using two aluminium cylinders mounted on a machined TUFNOL® base. Air and distilled water are used to calibrate the test cell over the measurement range of 1 MHz to 30 MHz. A measurement made at 10 KHz using laboratory grade conductivity calibration solution was used to check the conductivity equation.

Once calibrated, the test cell can be used to give a frequency profile of the ground parameters across the HF band. This profile can be used to calculate skin depth and relative wave attenuation in the ground and, via antenna modelling software using the Sommerfeld/Norton ground model, the expected gain and impedance of an antenna. The expected antenna gain can then be used to calculate the electric field intensity surrounding the HF antenna. No measurements have been made to compare the NEC4 simulated antenna gain against an actual antenna installed on the ground where the ground electrical parameters have been measured. This work is to be carried out at a later date.

While it is agreed that the disturbed ground packed into the test cell with a ramming rod is not the same as that which is undisturbed, it is felt the accuracy of the calibrated co-axial test cell configuration outweighs the potential error induced through disturbing the ground to measure the ground electrical parameters.

4. Acknowledgements

The sole responsibility for the accuracy of any technical writing lies with its author. Information obtained from references or discussions with colleagues is still the responsibility of the author for it was the author's decision to use or reject such information. With this in mind, this author wishes to acknowledge the contributions made to this document by the following people.

Dallas Taylor:- for bringing to my attention the need for a reliable and repeatable way of measuring ground parameters to correctly calculate antenna gain so that the HF noise E field intensity can be more accurately measured.

Dr. Stuart Anderson, Ian Coat and **Dr. Anthony Szabo:-** for vetting the document and their many suggestions which helped to clarify the test cell's calibration procedure.

5. References

1. G. H. Brown, R. F. Lewis and J. Epstein, "Ground Systems as a Factor in Antenna Efficiency", Proceedings of Radio Engineers, Volume 25, number 6, June 1937.

2. Melvin M. Weiner, (2003) "Monopole Antennas", ISBN:- 0-8247-0496-7. Published by Marcel Dekker, 270 Madison Avenue, New York, NY 100126.

3. J. C. Logan and J. W. Rockway, "Dipole and Monopole Antenna Gain and Effective Area for Communications Formulas", Technical Report 1756 Sep. 1997, Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA 92152-5001.

4. "IEEE Guide for Measurements of Electromagnetic Properties of Earth Media", (June 2002), IEEE Std. 356-2001

5. W. Martinsen (2003) "Construction Techniques for LC Highpass and Lowpass Filters used in the 1MHz to 1GHz Frequency Range", DSTO technical note DSTO-TN-0531

6. "Reference Data for Engineers Radio, Electronics, Computer, and Communications" (2002) ninth edition, ISBN:- 0-7506-7291-9.

7. Constantine A. Balanis, (1989) "Advanced Engineering Electromagnetics" LCCCN 88-33846

8. CCIR report 322-3, (1988) "Characteristics and Applications of Atmospheric Radio Noise Data"

9. John D. Kraus and Ronald J. Marhefka, "Antennas For All Applications", (2002), Published by McGraw-Hill Companies, Inc., ISBN:- 0-07-232103-2

10. "The ARRL Antenna Handbook" 19th edition (2000), ISBN:- 0-87259-804-7

Appendix A: Converting S_{11} (REAL) and S_{11} (IMAGINARY) into *R* and *jX* or the reverse

Some network analysers save the plot data in the S_{11} (REAL) and S_{11} (IMAGINARY) format where S_{11} (REAL) and/or S_{11} (IMAGINARY) can be positive or negative. It can be converted into *R* and *jX* series format by implementing the following equations via an EXCEL spreadsheet.

$$R = Z_o\left(\frac{1 - S_{(R)}^2 - S_{(I)}^2}{\left(1 - S_{(R)}\right)^2 + S_{(I)}^2}\right)$$

$$jX = Z_o\left(\frac{2S_{(I)}}{\left(1 - S_{(R)}\right)^2 + S_{(I)}^2}\right)$$

$$S_{(R)} = \frac{R^2 - Z_o^2 + jX^2}{\left(R + Z_o\right)^2 + jX^2}$$

$$S_{(I)} = \frac{2jXZ_o}{\left(R + Z_o\right)^2 + jX^2}$$

where:- Z_o = normalised impedance, usually 50 Ω
$S_{(R)}$ = magnitude of S_{11} (REAL) Cartesian coordinate
$S_{(I)}$ = magnitude of S_{11} (IMAGINARY) Cartesian coordinate
R = resistance (Ω)
jX = reactance (Ω)

This page is intentionally blank

Appendix B: The inverted monopole, buried transmission line and the Wenner Array

The inverted monopole is a metallic rod which has been hammered into the ground and a metallic ground mat placed on the ground/air interface. All vegetation must be removed from the surface of the ground and the ground surface made flat. Weights are usually placed on top of the ground mat to press the mat as close to the ground surface as possible. Air between the ground mat and the ground introduces errors in the measurement. The inverted monopole antenna is an unbalanced antenna and does not require a balun between the vector network analyser (VNA) and the antenna. Distributed parameter measurements are first made at RF frequencies with the rod and ground mat in free space for calibration purposes, then the rod and mat are installed as in Figure B1 to measure the ground parameters.

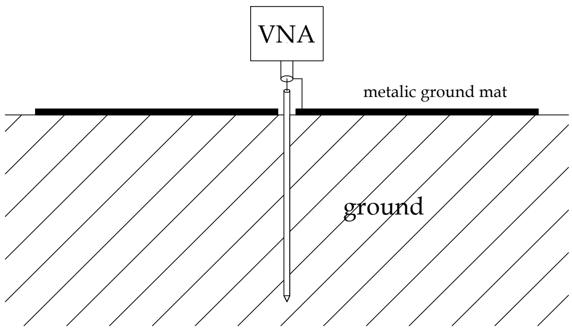


Figure B1:- The inverted monopole antenna

The buried parallel wire transmission line is two rods of equal length hammered into the ground with a known separation between the rods. The parallel rods act as an open circuit balanced transmission line and therefore require a balun between it and the VNA. Like the inverted monopole, a measurement is made at RF frequencies with the line in free space to calibrate the line, then it is inserted into the ground to measure the ground parameters. Care must be taken when pounding the rods into the ground that they remain perfectly parallel to one another.

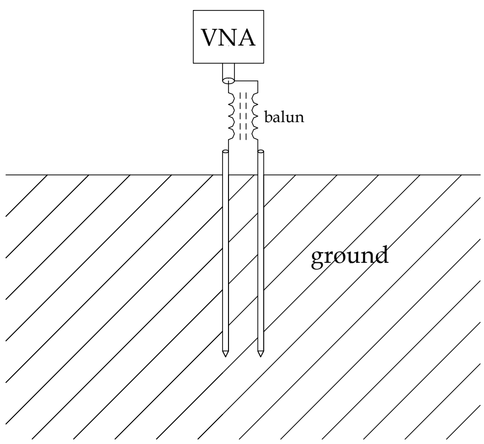


Figure B2:- buried parallel wire transmission line

The Wenner array which is usually a linear array of 4 rods equally spaced in which a low frequency voltage generator is connected between the outer pair of rods and an AC volt meter connected between the inner pair. The AC voltage generator can be the secondary winding of a step-down mains transformer. The current flowing through the ground is calculated by the voltage drop across the current sensing resistor. The current flowing through the ground's distributed resistance creates a voltage drop which is measured by the high impedance AC volt meter connected between the inner pair of rods. The ground resistance between the inner two rods is readily calculated by Ohm's law. The Wenner array is primarily used to measure ground resistance.

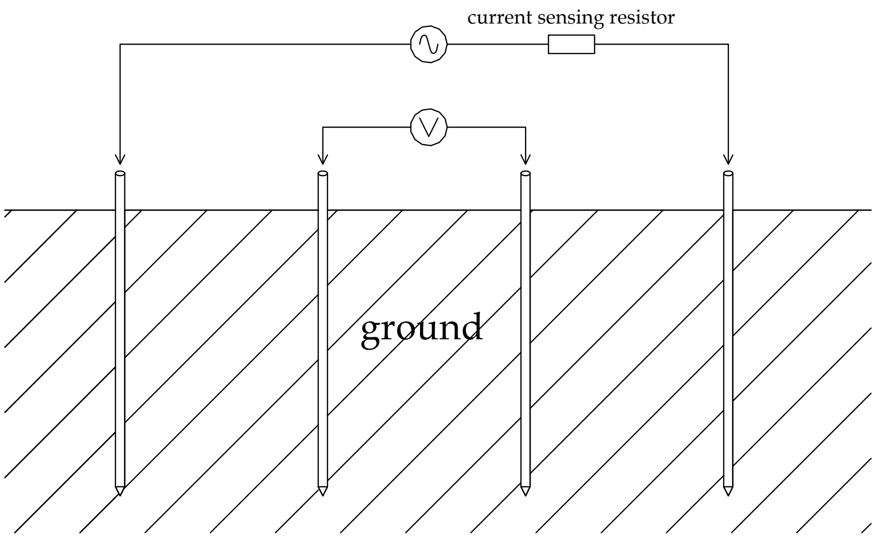


Figure B3:- the Wenner array

All of the above require the pounding of metallic rods into the ground. These rods have been observed to flex slightly at the moment the hammer makes contact with the rod. This flexing creates a small air gap between surface of the rod and the ground that it is being pounded into. It is not clear what effects this air gap may have on the measured data. Another unknown is what effect the seismic shock waves generated in the ground through the pounding of the rods has on the natural crystalline structure that forms within ground that has not been disturbed for some time.

Both the inverted monopole and the parallel wire transmission line can be used to measure the relative dielectric constant of the ground provided the effects of unwanted reactances are compensated for. What is not clear are the dimensions of the effective cubic volume of ground that the measurements are taken over so that the measured conductivity can be appropriately scaled to the required unit cubic volume, usually a cubic metre. Such a calibration could be carried out at some low frequency, 10KHz or less but not at DC, using a large volume of still water, such as a backyard swimming pool, which has been suitability treated to a known conductivity. A linear scaling factor can then be applied. It should be noted the co-axial test cell described in the main text only required one litre of laboratory grade conductivity solution for its conductivity calibration.

Appendix C: Approximating the gain of a vertical monopole antenna using data from the co-axial test cell

If antenna modelling software is not available then the gain of a monopole antenna can be approximated using equations (C1) and (C2). It uses the gain pattern of a monopole antenna mounted on a perfect ground plain as a starting point, then modifies it with the calculated vertical reflection coefficients of the ground [10, ch. 3, pg. 8].

$$dBi = A_{(dBi)} + 20Log_{10}\left(0.5\cos\psi\left(1+\frac{k^{'}\sin\psi-\sqrt{k^{'}-\cos^{2}\psi}}{k^{'}\sin\psi+\sqrt{k^{'}-\cos^{2}\psi}}\right)\right) \quad \text{(C1)}$$

$$k^{'} = \sqrt{k^{2}+\left(\frac{18000G}{f}\right)^{2}} \quad \text{(C2)}$$

where:- k = relative dielectric constant of ground
G = ground conductance (S/m)
f = frequency (MHz)
ψ = elevation angle (degrees)
$A_{(dBi)}$ = 5.1 = gain of monopole antenna on a perfect ground plane (dBi)

The data of the ground parameters, as measured by the co-axial test cell on 03-Apr and 11-Jun-2009, were entered into an EXCEL spreadsheet together with equations (C1) and (C2) and used to produce the plot seen in Figure C1. The same colours as seen in Figure 10 of the main text have been used to represent the data in Figure C1. By comparing Figure 10 in the main text with Figure C1, it can be seen that the above equations give a reasonable approximation in the absence of the more complex Sommerfeld/Norton ground model.

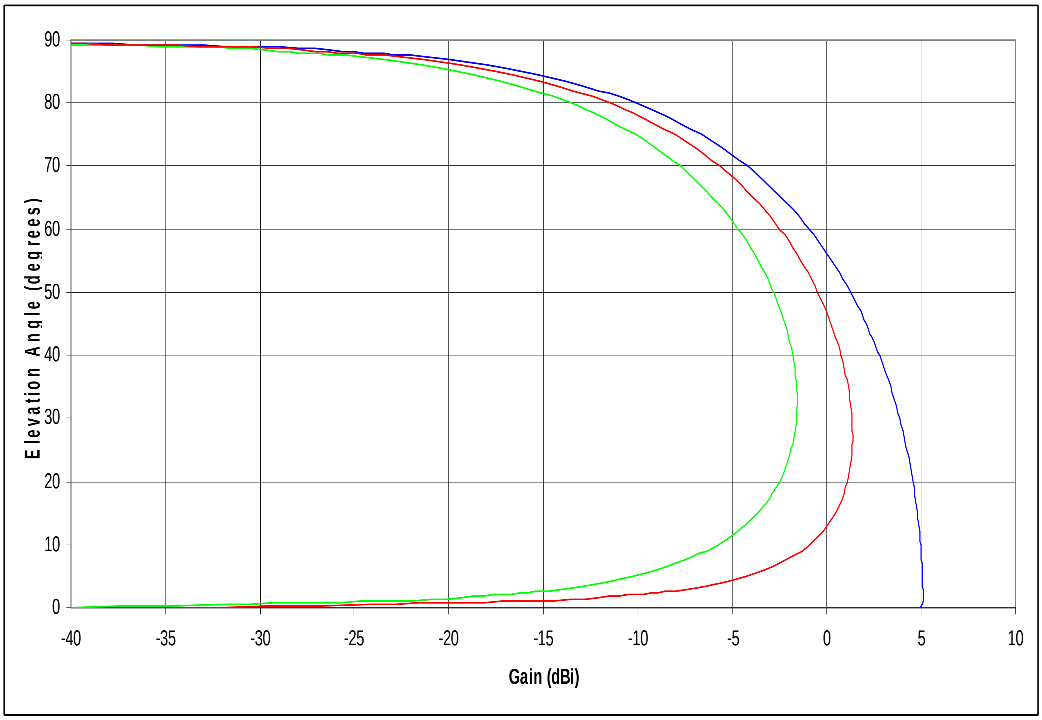


Figure C1: *Simulated gain in dBi of the 6.5 m resonant monopole at 11.27 MHz using the above equations (C1) and (C2)*
Blue:- on a perfect ground plane, maximum gain 5.1 dBi at 1 degree elevation
Red:- (after rains) with ε_r = 30.3 and σ = 10.5 mS/m, maximum gain is 1.4 dBi at 27 degrees elevation
Green:- (drought) with ε_r = 4.3 and σ = 0.19 mS/m, maximum gain is -1.6 dBi at 33 degrees elevation

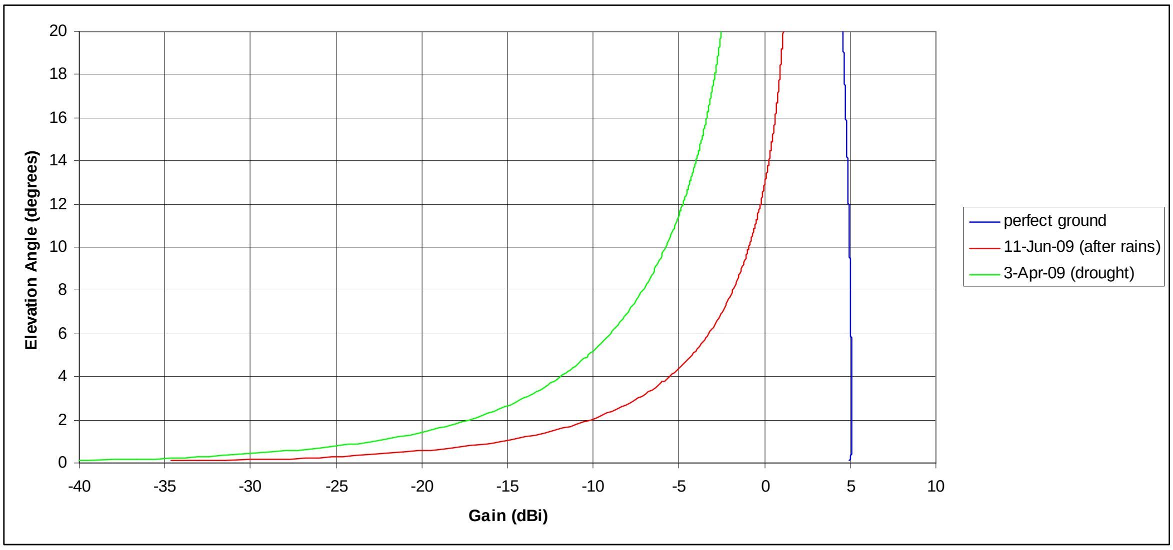


Figure C2: *Zoomed into the first 20 degrees in elevation of the simulated gain as seen in Figure C1*

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT) N/A

2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
A Co-axial Test Cell for Measuring the Electrical Parameters of a Sample of the Ground Surrounding a HF Antenna Installation	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
W. Martinsen	DSTO Defence Science and Technology Organisation P.O. Box 1500 Edinburgh, South Australia, 5111, Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TR-2555	AR-015-010	Technical Report	June 2011

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
E 8709/8/17 pt 1	INT 05/201	ASCP	26	10

DSTO Publications Repository	14. RELEASE AUTHORITY
http://dspace.dsto.defence.gov.au/dspace/	Chief, Command, Control, Communications & Intelligence Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitation

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO Research Library Thesaurus

High frequency; Electrical measurement; Antennas; Testing; Noise measurement; Antenna gain

19. ABSTRACT
This report describes development of a co-axial test cell for measuring the electrical parameters of ground samples taken from an antenna site. The accuracy of the test cell has been verified by measuring the relative dielectric constant of air and distilled water over the HF frequency range. The resistivity measurement equation has been confirmed by measuring a calibrated test solution at 10 KHz.